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FEASIBILITY STUDY OF A NEUTRON SOURCE AT THE DAΦNE BEAM TEST FACILITY

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Abstract

There is an increasing interest in our scientific community to have a neutron source at the INFN for detector calibrations and physics investigations in different domains. In this report we describe the preliminary study that we have done to estimate the feasibility of a photo-neutron source at the Daϕne Beam Test Facility. The physics of the neutron photo-production is introduced and synthetically discussed in the first 2 sections. In the following ones we show the details of the Monte Carlo simulations and the comparison of these results with some important semi-empirical correlations. Finally, we reported some values of the integrated neutron flux, that we expected to have, when a 510 MeV electron beam impinges on a suitable target, made of high Z material.

1 Neutron Photoproduction: physics principles

High energy electrons impinging on a target produce a continuous spectrum of bremsstrahlung photons. These gamma rays can generate neutrons via photo-nuclear reactions As the nucleons are bounded in the nucleus, the (γ,n) reaction will occur only if the the γ-ray energy is at least equal to the bending energy of the neutron target: photoneutron production is essentially a threshold process (see figure 1).

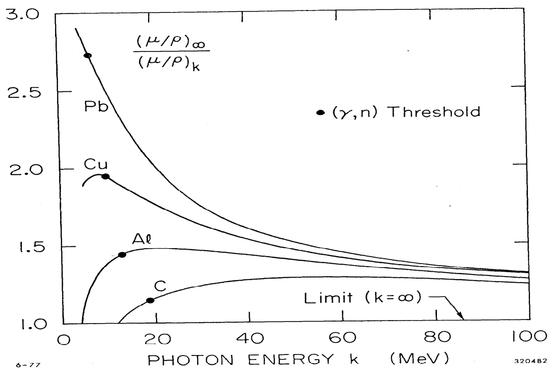

Figure 1: *Threshold for photoneutron production for different materials.*

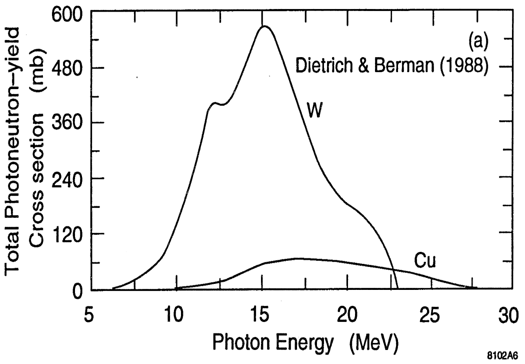

Figure 2: *Typical photoneutron cross section behaviour for medium (Cu) ans high Z (W) materials.*

Photonuclear interaction is mainly the result of three specific processes:

- GDR-Giant Dipole Resonance. The electric field of the photon transfer its energy to the whole nucleus by inducing an oscillation (known as giant resonance oscillation), which leads to a relative displacement of tightly bound neutrons and protons inside the nucleus. Absorption of the incident photons excites the nucleus to a higher discrete energy state and the extra energy is emitted in the form of neutrons. For heavy nuclei, the excited nucleus comes into ground state by emission of neutron n (γ,n). Some contribution from double neutron emission (γ,2n) is also possible for higher photon energies. Because of the presence of the large Coulomb barrier, proton emission is strongly suppressed for heavy nuclei (on the contrary, below Z=20 the proton yield is in general larger than the neutron yield).

- QD-Quasi-Deuteron. When photon energy is greater than 35 MeV, the cross section for the giant resonance neutron production decreases rapidly. At $35 \leq E \leq 140$MeV, the photoneutron production is due to quasi deuteron effect. In this process, he incident photon interacts with the dipole moment of a neutron-proton pair inside the nucleus rather than with the nucleus as a whole.

- Intranuclear Cascade. Above 140 MeV photoneutrons are produced via photo-pion production.

The photoneutron cross section exhibits the behaviour shown in figure 2: it starts to rise for $E \geq E(th)$, reaches a maximum and after decreases. The cross section has a maximum at photon energy between 13-18 MeV for heavy nuclei and 20-23 MeV for light nuclei ($A \leq 40$). The lower Z materials (Cu, Al) generally have higher thresholds and broader peaks which occur at higher photon energies. The emission of gamma rays is almost proportional to the atomic number Z of the target material and to the energy of the particle.

1.1 Monoenergetic photoneutron source

The action of gamma rays of medium energy (about 2 MeV) on the nuclei of deuterium and beryllium, both of which are normally used as moderators, yelds essentially monoenergetic neutrons. The reaction are:

$$ {}_1{}^2H + \gamma \rightarrow {}^1{}_1H + {}^1{}_0n \tag{1} $$

$$ {}_4{}^9Be + \gamma \rightarrow {}^2{}_4He + {}^1{}_0n \tag{2} $$

It is because the bending energy is exceptionally low in deuterium (2.2 MeV) and beryllium (1.6 MeV) that these substances are generally used in (γ, n) sources. For photons of a given energy, the neutrons obtained are monoenergetic, the energy being equal to the difference between the photon energy and the neutron binding energy in the target nucleus. For gamma ray energies that exceed this minimum, the corresponding neutron energy can be calculated from:

$$ E_n(\theta) \simeq \frac{M(E_\gamma + Q)}{m + M} + \frac{E_\gamma[(2mM)(m+M)(E_\gamma + Q)]^{1/2}}{(m+M)^2} cos\theta \tag{3} $$

where θ is the angle between gamma photon and neutron direction, E_γ is the gamma energy (assumed $\leq 931 MeV$),Q is the bending energy of neutron in the nucleus, M is the mass of the recoil nucleus x c^2 and m the mass of neutron x c^2. The relatively small kinematic spread obtained from eq.3 by letting the angle θ vary between 0 and π broadens the neutron energy spectrum by only a few percent. The main disadvantage of this kind of photoneutron sources is the fact that high intensity gamma rays fluxes are necessary to produce only few neutrons.

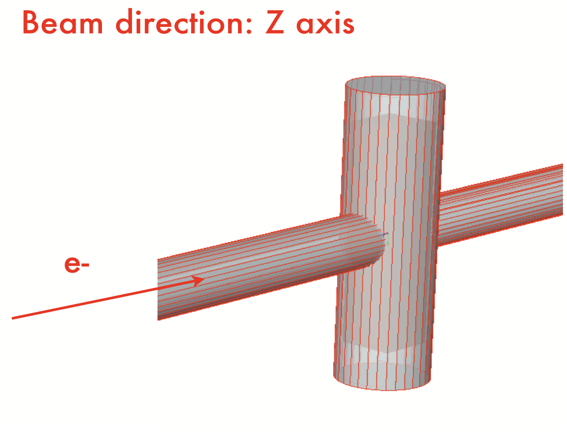

Figure 3: *Monte Carlo model: the copper target is located inside the aluminum transfer line.*

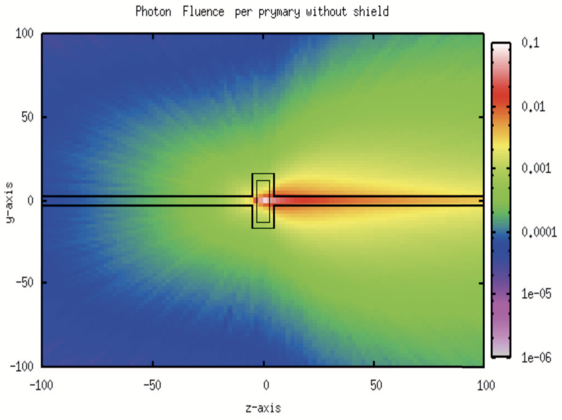

Figure 4: *Photon Fluence distribution [n/cm2/ prymary] around the BTF target.*

2 Preliminary estimation of neutron rate achievable at the Daϕne Beam Test Facility

The results of preliminary study to realize a neutron source at the $Da\phi ne$-Beam Test Facility will be presented in what follows. The idea essentially consists in making the electron beam to impinge on a suitable target that will be located in the BTF experimental hall at the end of the transfer line, in such a way to produce a cascade shower of bremsstrahlung photons that will have energy spectrum end point equals to the electron beam energy. The produced photons can be absorbed by the nuclei of the target producing neutrons.

2.1 Photon Source

Typical bremsstrahlung photon spectra are shown in figure 5: these have been obtained as result of Monte Carlo simulation (FLUKA code [1]) of the photon spacial distribution (see fig.4) and spectra around the BTF energy degrader [3]. The BTF energy degrader is a copper target located at the beginning of the BTF transfer line: it has a square cross section of about $3X_0$, whereas the biggest dimension of about $12X_0$ is perpendicular respect to the electron beam direction and lies in the vertical plane.

These calculations have been done in the frame of the study and design of the shield for the BTF target([2]), as need for reducing the background along the BTF transfer line and in the experimental hall, where the user's experiments are hosted.

The energy spectrum of the radiated photons ranges from 0 to the energy of the incident electrons and the number of photons in a given energy interval is approximately in-

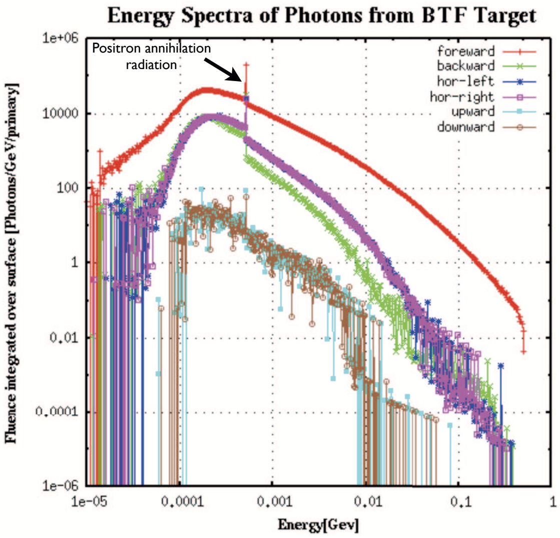

Figure 5: *Energy Spectrum of bremsstrahlung photons emerging in various direction from a copper target (6x6x25 cm) when a 510 MeV electron beam impinges on it.*

versely proportional to the energy (fig 5). As expected for, the calculated bremsstrahlung spectra are noticeably more energetic (i.e. ‘harder’) at forward angles respect to the other directions.

2.2 Neutron Source

The rate of neutrons produced depends essentially by the following factors:

- Beam Power released in the target
- Atomic Number, Z, of the target nuclei
- Energy of the electron in the beam

The maximum energy that the electrons can reach in the $Da\phi$ne Linac is 800 MeV, anyway for all the calculations the nominal value of 510 MeV has been considered. A first estimation of the maximum beam power that can be released on a target in BTF, if the $Da\phi ne$ beam could be entirely transported in the BTF, is the following one:

$$P_{beam} = N \cdot f \cdot E = 0.04\ kW \tag{4}$$

where $N \simeq 10^{10} particles/bunch$, repetition injection rate f=50 Hz and E=510 MeV.

Since the old safety limit of 10^3 e^-/s (or e^+/s) as maximum admissible beam intensity in BTF has been removed by the National Regulatory Authority, it is now possible to bring in BTF hall up to 10^{10} e^- /s. This has encouraged to advance in the study of feasibility of neutron source in BTF.

A semi-empirical correlation linking the neutron yield on target and the released beam power has been determined by Swanson[5] at Slac and could be useful for having an initial estimation of the maximum neutron yield, even if, as declared in the cited article, this could be little bit underestimated respect to the real value. Swanson studied the photoneutron production using high energetic electron beam. He found that above a certain energy the neutron yield becomes nearly proportional to the incident power regardless of the energy per incident particle. He derived a formula that allows to estimate the average trend of the neutron yield, at high electron energies (greater than 10 MeV), as function of the atomic number of the target material:

$$\gamma = 9.3 \cdot 10^{10} Z^{0.73\pm0.05} \left[\frac{n}{s \cdot kW}\right] \tag{5}$$

Using the Swanson formula and the related curves reported in figure 6, a preliminary estimation of the neutron rate in BTF can be derived for different materials and the results are illustrated in the table-2.2.

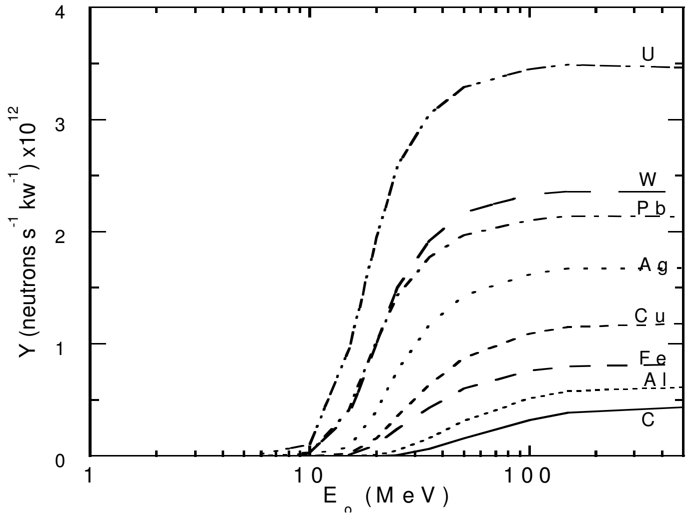

Figure 6: *Neutron yield for unit beam power versus the electron beam energy* E_0.

It is important to remark that these values can be applied for targets enough tick that all the energy of the ensuing electromagnetic cascade is absorbed in the target (that is for

$table\ 2.2 : P_{beam} = 0.04kW@$ 510 MeV

Target Material	Neutron Rate [n/s]	Conversion Rate
Al	$2 \cdot 10^{10}$	$4 \cdot 10^{-2}$
Cu	$4 \cdot 10^{10}$	$8 \cdot 10^{-2}$
Pb	$4 \cdot 10^{10}$	$16 \cdot 10^{-2}$

thickness greater than $10X_0$, where X_0 is the radiation length).

The energy spectrum of the neutron depends on the thickness of the target, so that an optimum value for which the neutron flux is maximum at a defined energy can be found. The spectrum of the photoneutrons generated by high energy electron (greater than 10 MeV) on a high Z target can be well described by a maxwellian distribution[6]:

$$\frac{dN}{dE_n} = k \cdot \frac{E_n}{T^2} e^{-\frac{E_n}{T}} \tag{6}$$

in which T is a nuclear temperature (MeV), which is characteristic of the particular target nucleus and represents the most probable energy of the neutrons generated. Values of T generally lie in the range from 0.5 to 1.0 MeV for high Z materials. It must be taken into account that the spectrum of photoneutrons can be degraded rapidly in heavy metals so each spectra should be accurately referred to a specific target thickness. Although the spectra degradation is significant, the attenuation of neutron fluence is small, because the capture cross sections of heavy metals are small down to thermal energies.However a more accurate calculation of the photoneutron spectra can be obtained only by Monte Carlo simulation, taking into account: the geometry of the target, the realistic spot size and energy distribution of the impinging beam, the effective material composition and so on.

3 Monte Carlo Theoretical prediction: more accurate radiation source term and neutron spectra calculation

Monte Carlo simulations have been performed up to now by FLUKA code[1], even if an extensive use of Geant4[7] and MCNPX[8] has been foreseen and simulations are in progress in order to give a more accurate estimation of the neutron rate as well as to study the neutron energy spectra and spatial distribution as function of the thickness of the chosen material. In fact, the energy spectrum of the neutron depends on the thickness of the target, so that an optimum value for which the neutron flux is maximum at a defined energy can be found.

Neutrons in BTF can be produced by photo-absorption of continuous bremsstrahlung photons generated when high energy electrons (or positrons) impinge on a suitable target. Above a certain energy (typically 100 MeV) of the beam electrons (or positrons), the neutron yield from photo-absorption becomes quite proportional to the incident power, regardless the energy of the incident particles.

Several calculations have been made for choosing the best material in terms of yield of neutrons produced per electron or positron impacting on a “infinitely” thick target[1].

According to the work made from Swanson[5] at SLAC, concerning the neutron photoproduction in electron accelerators, as preliminary calculations with FLUKA we chose to study as target material the following high Z materials :

- lead (rad.length 6.37 g cm^{-2}),
- tantalum (rad.length 6.82 g cm^{-2}),
- tungsten (rad.length 6.72 g cm^{-2}).

Suitable materials for optimized target for photoneutron production

Material	Density[g/cm3]	Radiation length X_0 [cm]
W	18.2	0.38
Ta	16.6	0.41
Pb	11.4	0.56

For sake of semplicity, just as starting point, the geometry of the target has been assumed to be spherical with a radius $R \simeq 10X_0$. In figure 7 and 8 the spatial fluence and the energy spectrum for neutrons coming out from the lead target have been reported.

Up to 100 MeV the spectrum is described as a Maxwellian distribution with average around 1 MeV. Approaching the higher energies the Quasi-Deuteron effect adds a tail to the Giant resonance spectum. The slope becomes stepper as the incident electron energy is approached.

Similar results are obtained for the tungsten and tantalum case, even if some difference in the energy spectrum has been found as shown in figure 9. As expected the mean energy is lower in tungsten and tantalum target than in lead, due to a little moderation effect for higher density material. Moreover the maximum yield (neutron/primary) at the nuclear temperature is almost the same for W and Ta cases, while in case of the lead is consistently lower than the previous ones.

The main goal of these preliminary calculations consists in validating our Fluka predictions on the basis of Swanson semi-empirical correlations, that represent an important reference in this physics domain. Several cases have been tested and all of these show a good agreement between MC estimation and Swanson correlations: for

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[1] Thickness $\geq$10 radiation length X_0

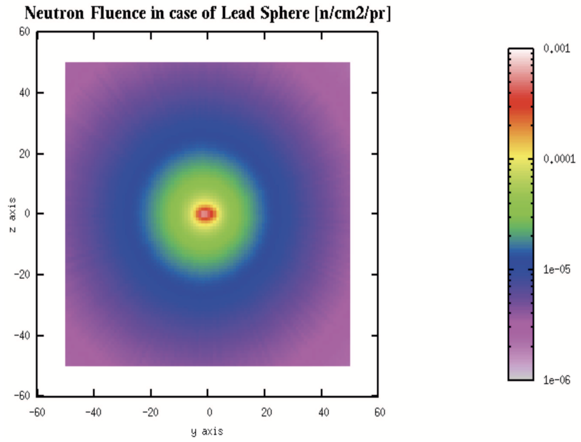

Figure 7: *Isotropic Fluence of photoneutrons exiting from a lead spherical target.*

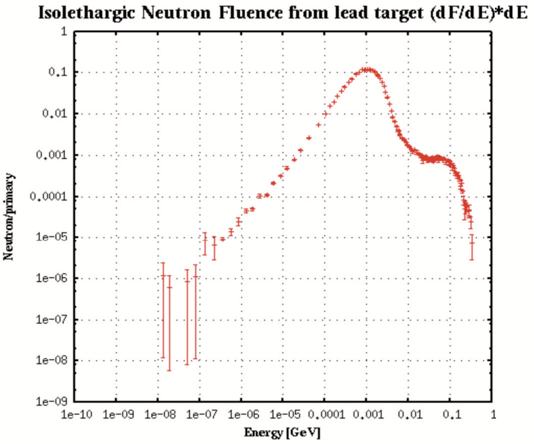

Figure 8: *Energy Spectrum of photoneutrons produced in a lead spherical target.*

example, Monte Carlo simulations for a lead sphere of $6X_0$ of radius by Fluka code give a neutron yield integrated on all the energy spectrum and on all the solid angle of $1.6826 \cdot 10^{-1}$neutron/primary, while the Swanson semi-empirical correlation([5],[9] gives $1.6 \cdot 10^{-1}$ neutron/primary.

The good agreement between Swanson estimations and Fluka predictions is resumed in table 3, where the maximum neutron yield (integrated over all the spectrum and all the solid angle) has been reported for different high Z materials. These results make us confident to have a reliable tool to estimate the neutron source term.

table 3: Neutron Yield [$\cdot 10^{12} n \ \ s^{-1} \ kW^{-1}$] for thick target and 510 MeV electrons

Target Material	Swanson semiempirical correlation	Fluka predictions
Lead	1.98	2.08
Tantalum	2.13	2.45
Tungsten	2.4	2.7

The maximum neutron rate should be obtained around 1 MeV (0.7 MeV), for which Fluka calculation gives the value of 0.1343 neutron/primary, on all solid angle (lead shere with R=10 X0). This means that if we bring $4.9 \cdot 10^{11} e-/s$ into the BTF experimental hall we should get by photoproduction, the following neutron rate per electron: $6.5 \cdot 10^{10}\ n/s$, over all the solid angle at ∼1 MeV.

4 Future Plans and Conclusion

There is an increasing interest of the International Scientific Community for neutrons applications (new detection techniques, fundamental physics,etc). Concerning INFN, the

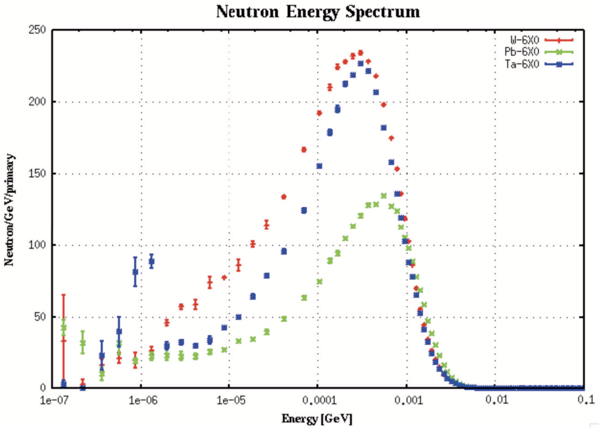

Figure 9: *Energy spectra of photoneutron produced in lead, tungsten and tantalum Target.*

realization of a neutron source could be useful for the following tasks:

- Determination of neutron detection efficiency of Kloe Detector (Klone experiment);
- Study of high intensity neutron source to measure nuclear cross sections by time of flight techniques (database improvements and applications on reactor physics and nuclear waste domain);
- Realization of a prototipe of a facility to calibrate detectors for neutrons to be employed in radioprotection and dosimetry (U.F. FISA);
- Study of GEM detectors application for neutron beam diagnos
- Applications on cryogenic detector for dark matter (Quenching Factor for WIMP);

In order to realize an experiment, with the final goal of studying the feasibility and effectiveness of a neutron source by photoproducion on high Z target at the Daϕne BTF, we started the ‘n@BTF’ project. Concerning this project, we have obtained preliminary estimation by Monte Carlo simulations of the maximum neutron rate and the enrgy spectra obtainable from a suitable target with the Daϕne BTF electron beam, taking care to validate the results by the comparison with well known and consolidated semiempirical correlations.

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